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The Effects of Sleep Deprivation on Spatial Disorientation

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Spatial disorientation is an inaccurate impression of one's position in space with respect to the earth's surface. As sleep loss is known to produce visual disturbances, this study was designed to investigate the effects of fatigue on aviator response to in-flight, disorienting events. Eight UH-60 rated aviators served as volunteer subjects. The subjects reported to the Laboratory at 1700 on Monday for inprocessing and baseline testing, retired at 2300, and awoke at 0700 on Tuesday. Throughout the day, aviators repeated one 6-hour practice test block three times. Each block included a 1-hour UH-60 simulator flight, objective and subjective measures of alertness, and several cognitive tests. To control for order effects, half of the subjects remained awake from 0700 Tue to 2300 Wed and were exposed to the disorienting events for the first time when they were sleep deprived. The other half of the subjects remained awake from 0700 Wed to 2300 Thu and saw the events first when they were fully rested. Analyses showed that nearly all measures of performance, to include mood, alertness, cognition, spatial orientation, postural stability, flight accuracy, and recovery from in-flight disorientation, were detrimentally impacted by fatigue.

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Aviators also reported a significant increase in oculomotor disturbances following fatigued simulator flights. New methods are being developed to assess the impact of visual disturbances on aviator performance during periods of extended operations.

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Introduction

Spatial disorientation (SD) is a fairly common in-flight phenomena. Disorientation in flight occurs when a pilot fails to correctly sense the position, motion or attitude of his/her aircraft or self with respect to the surface of the earth. While vestibular apparatus, proprioceptive receptors, kinesthetic receptors, hearing, and touch provide sensory input during flight, spatial orientation is largely a function of the visual system. Many studies have reported increases in visual disturbances such as blurred vision, double vision, faulty depth perception, and distortions in shape and size after extended periods of wakefulness. The primary purpose of this investigation was to establish the effects that fatigue might have on flight performance in aviators subjected to in-flight, disorienting events. In addition to flight performance, this study employed a variety of assessments to determine the effects of fatigue on central nervous system function, orientation problems, and cognitive, mood, and alertness measures.

Background

According to current Army doctrine, aviation units may be required to operate around the clock during times of conflict. Technological advances in night vision devices have removed many of the barriers associated with night operations. Due in part to these significant improvements, night helicopter operations now constitute a substantial component of the modern aviation mission. Continuous day-night operations provide obvious operational and tactical advantages on the battlefield (Department of the Army, 1989). Combining efficient day and night fighting capabilities across successive 24-hour periods places a significant strain on enemy resources and presents a clear tactical advantage for U.S. forces.

However, there are difficulties inherent in maintaining effective round-the-clock operations. Although aircraft can function for extended periods without adverse effects, human operators need periodic sleep for the restitution of both body and brain (Horne, 1978). Depriving humans of proper restorative sleep produces attentional lapses, slowed reaction times, and reduced arousal levels, all of which are associated with poor performance (Kjelberg, 1977a; b; c; Krueger, 1989). Tasks that place heavy demands on working memory, that call for sustained attention, or require creativity even for short durations are affected by sleep deprivation (Dinges and Broughton, 1989).

In general, tasks that require sustained concentration and vigilance, such as monitoring radar screens and control panels, are the most susceptible to the influences of sleep deprivation. Sleep deprivation produces periods of slow performance and periods of nonperformance or lapses. As the duration of sleep loss increases, the lapses increase in frequency and duration. Williams, Lubin, and Goodnow (1959) found that on a 10-minute monotonous vigilance test that is typically performed without difficulty, after one night of sleep loss, performance began to degrade within 7 minutes. On this same task, after 2 nights without sleep, the degradation began after 2 minutes. Hockey (1970a; b) has shown that sleep deprivation produces slower reaction times on tracking tasks, and subjects become more easily distracted and have difficulty concentrating on sustained attention tasks such as card sorting.

Several early sleep deprivation studies that used 72- to 96-hour periods of sleep loss reported increases in visual disturbances (Bliss, Clark, and West, 1959; Katz and Landis, 1935; Tyler, 1947). After about 30 hours of wakefulness, subjects in these studies had begun to complain of periods of blurred vision. Additionally, many acknowledged double vision when asked to focus on small targets for brief periods of time. Between 40 and 60 hours of sleep loss, several subjects reported brief periods of visual distortion during which depth perception, shape, size, and position constancies were impaired (Morris, Williams, and Lubin, 1960). There were also reports of other perceptual anomalies, including spatial disorientation, where subjects felt unable to correctly judge the position of themselves, objects, and other people.

Such misperceptions in flight can have disastrous effects, as summarized in retrospective studies of U.S. Army helicopter accidents involving SD (Braithwaite, Groh, and Alvarez, 1997; Durnford et al., 1995). In the most current review, Braithwaite, Groh and Alvarez (1997) reported that SD was a major or contributory factor in 30 percent of all class A through C accidents. Comparisons by these authors have shown that the outcomes of accidents involving SD were much more severe than those not involving SD. During the period 1987-1995, 36% of SD accidents were Class A compared to 18% of non-SD accidents. The average monetary cost of the SD accidents was more than double (1.62 million) that of the non-SD accidents (0.74 million), as was the loss of life per accident (0.38 vs. 0.14).

In a recent survey of U.S. Army rotary-wing aircrew, 78 percent of the respondents reported suffering SD to some degree during their careers (Durnford et al., 1996). While the percentage in Durnford et al.'s study was quite high, other surveys have reported career incidents ranging from 90-100 percent (Clarke, 1971; Durnford, 1992; Eastwood and Berry, 1960; Steele-Perkins and Evans, 1978; Tormes and Guedry, 1974). As SD appears to be a very common and very costly aviation phenomenon, the British Army began using a specially designed spatial disorientation sortie during helicopter training in 1982. According to Braithwaite (1997), the SD accident rate in the British Army Air Corps has dropped significantly since the inception of this training program. During the period 1971-1982 (prior to sortie training) pilots averaged 2.04 accidents per 100,000 flight hours. This rate dropped to 0.57 accidents per 100,000 flight hours following the onset of the SD training (1983-1993). Unfortunately, changes in aircraft operations (single to two pilot operators) and instrumentation (radar altimeters) also occurred during this time frame (mid 1980's). These confounding factors make it difficult to apportion the decrease in SD accidents to improved training or aircraft.

In addition to training, Braithwaite et al. (1998) examined the use of a novel display to assist in overcoming disorienting phenomenon. These researchers tested recovery from unusual attitudes using a flat panel display designed to reduce cognitive workload, improve flight accuracy, and aid in recovery from disorienting episodes. The novel display was quite successful in enhancing flight control. However, subjects in this protocol were required to close their eyes while the computer put them in an unusual attitude from which they attempted to recover. While this study did provide much useful information about recovery from disorienting episodes, during real flight, pilots will not be given a warning that a disorienting event is about to occur.

LeDuc et al., (1999) showed that by producing divergent visual and vestibular cues at certain points along the flight path, it was possible to produce disorientation in a UH-60 simulator. Of the 63 disorienting events presented (21 aviators; 3 events each), all interfered to some degree with pilot performance, as seen in the reaction times of flight parameter recovery. On average, it took 54 seconds to recover from the pitch and roll and 122 seconds to recover from the drift. It is very likely that the recovery time for the drift was considerably longer than it was for the other two maneuvers as the illusion was presented during a hover, and it is more difficult to reestablish the parameters for a stationary hover than to correct in-flight deviations.

Using this flight profile, it will be possible to examine the impact that various stressors common in the aviation community may have on spatial disorientation. As fatigue is one of the more common stressors in the aviation community, studies dating as far back as the 1930's have repeatedly demonstrated that sleep loss can decrease ones ability to concentrate, produce visual illusions, and induce disorientation. The purpose of this study was to examine the impact of fatigue on aviator response to disorientation in flight.

Methods

Subjects

Eight male UH-60 rated aviators, with current flight physicals, were recruited to reside in the U. S. Army Aeromedical Research Laboratory test facility for a period of 5 days each. The age range of the subjects was 27-48 years (mean=32.6). Every effort was made to test both male and female subjects; however, no female aviators volunteered for this study. Aviators remained in the Laboratory from check-in on Monday until release on Friday. Subjects were not permitted to consume alcohol, beverages with caffeine, or any type of medication (other than acetaminophen, ibuprofen, or naproxen sodium, as approved by the medical monitor) for the duration of the protocol. Participants who indicated they were caffeine users during initial telephonic interviews were asked to significantly reduce or completely eliminate caffeine consumption beginning several days prior to the study.

Apparatus

Simulator sickness evaluations

Aviators were asked to complete a Motion Sickness Questionaire (MSQ) (Gower and Fowkles, 1989; Lane and Kennedy, 1988) after each flight. The MSQ is a self-report form consisting of 28 items that are rated by the participant in terms of severity on a 4-point scale. Although the full MSQ was given, only an abbreviated version, the 16 item Simulator Sickness

Questionnaire (SSQ), was scored. The answers were automatically computed and stored for later analysis.

Mood evaluations

The subjective evaluations of changes in mood were made with the Profile of Mood States (POMS) (McNair, Lorr, and Droppleman, 1981). The POMS is a 65-item computerized test that measures affect or mood on 6 scales: 1) tension-anxiety, 2) depression-dejection, 3) anger-hostility, 4) vigor-activity, 5) fatigue-inertia, and 6) confusion-bewilderment. The answers were automatically scored by computer and stored for later analyses.

Sleepiness evaluations

Subjective sleepiness was measured using the Visual Analog Scale (VAS). The VAS consists of eight 100-mm lines centered over the adjectives “alert/able to concentrate,” “anxious,” “energetic,” “feel confident,” “irritable,” “jittery/nervous,” “sleepy,” and “talkative” (Penetar et al., 1993). At the extremes of each line, “not at all” and “extremely” were printed. Scores consisted of the distance of the subject’s mark from the left end of the line in mm.

Objective sleepiness was measured using the Repeated Test of Sustained Wakefulness (RTSW) (Hartse, Roth, Zorick, 1982). During the RTSW, subjects were instructed to remain awake in a darkened room. Electroencephalography data were monitored for up to 20 minutes using a Nihon Kohden EEG to objectively determine if the subjects successfully remained awake. Subjects were immediately awakened and removed from the room if they fell asleep. Records were scored in terms of the number of minutes from lights out until sleep onset (up to 20 minutes).

UH-60 simulator

All simulator flights were conducted in an NUH-60 flight simulator that had computer-generated visual displays (programmed for dusk conditions) and a multi-channel data acquisition system for analyzing various parameters of flight such as heading, airspeed, and altitude control. Digitized flight performance data were collected and stored on a VAX computer system for subsequent statistical evaluation. Disorienting events (drift, roll, or pitch) were produced by creating divergent visual and vestibular cues at certain points along the flight path.

Psychomotor and cognitive evaluations

Changes in basic psychomotor and cognitive abilities were examined with the: 1) WOMBAT (Aero Innovations Inc.*), 2) Multi-Attribute Task Battery (MATB), and 3) Synthetic Work Battery (SYNWORK). The primary task of the WOMBAT consisted of a single-axis nonstereotypical left-hand tracing task and a dual-axis right-hand stereotypical tracking

*See manufacturers list at appendix.

task. Three secondary tasks included a 3-D rotation and matching task, a sequential quadrant-location task, and a two-back delayed sequential-digit-canceling test. The MATB required that subjects perform a tracking task concurrent with monitoring simulated indicators of fuel levels, pump status, engine performance, and other aspects of "aircraft status." Subjects were also required to periodically change radio frequencies. The SYNWORK consisted of a Sternberg memory task, an arithmetic task, a visual monitoring task and an auditory monitoring task. These were presented simultaneously in four quadrants of the computer screen. The computer automatically calculated data on speed and accuracy. These tests were administered via a Gateway Pentium computer with a 13-inch color monitor.

Desktop flight simulation

The desktop flight simulation task (MINISIM) consisted of the Microsoft Flight Simulator 4.0®, combined with a custom-designed, timed flight course (Microsoft Aircraft and Scenery Designer®*). This task was run on an IBM 486 computer with VGA graphics. Flight control was established via a Virtual Pilot flight yoke (CH Products®*) with system interface, using a keyboard.

Balance master

Orientation problems were assessed with computerized dynamic posturography using the Neurocom Pro Balance Master®* system. This system offers a quantitative assessment of a person's postural movements in relation to balance. The system has a moveable computerized force plate, which measures, responds to, and dynamically provokes the subject's postural movements. All measurements were calibrated to each subject's height and weight. Software protocols used the force input and height data to calculate and record the position of the subject's center of gravity.

Procedure

General

Volunteer screening questionnaires were filled out through telephone or e-mail using a standardized script. These interviews were conducted at least 1 week prior subject arrival. Information was provided to the medical monitor. Subjects were asked to telephone the medical monitor if any changes in health status occurred prior to reporting to Fort Rucker, AL. Subjects reported to the Laboratory at 1700 on Monday, and filled out the informed consent statement and other required paper work. Aviators verified the status of the health information previously obtained on the volunteer screening questionnaire. Had any change in health status occurred, it would have been reported to the medical monitor.

After inprocessing, volunteers were given a brief tour of the Laboratory, followed by an initial posturography session, a WOMBAT introduction, and dinner prior to electrode hookup. Subjects retired at 2300. Wake-up on Tuesday was at 0700. Throughout the day, aviators repeated one 6-hour practice test block three times. Each block included a 1-hour UH-60 simulator flight, objective and subjective measures of alertness, and several cognitive tests. To control for order effects, half of the subjects remained awake from 0700 Tue to 2300 Wed and were exposed to the disorienting events for the first time when they were sleep deprived. The other half of the subjects remained awake from 0700 Wed to 2300 Thu and saw the events first when they were fully rested.

During the deprivation night, subjects had one baseline session that began at 0100 and three fatigued test sessions that began at 0700, 1300, and 1900. Three rested test blocks were conducted at 0700, 1300, and 1900, following 8 hours of sleep. One in-flight, disorienting event occurred during each of the fatigued and rested simulator sessions. All subjects retired at 2300 on Thursday. Subjects awoke at 0700 on Fri, were debriefed, and released at 0730. See table 1 for a complete testing schedule.

SSQ

The SSQ was given every 3 hours beginning at 0715 and immediately after the conclusion of each simulator flight. This test took approximately 5 minutes to administer and yielded scores on the factors of nausea, oculomotor disturbance, disorientation, and total symptom severity.

Mood evaluation

The POMS was given immediately following the SSQ. The subjects were presented with a series of 65 words which described mood states; and for each "mood state," were asked to indicate on a computerized answer sheet how well it described the way they were presently feeling. This test took approximately 5 minutes to administer and yielded scores on the factors of tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment.

Sleepiness evaluations

The VAS was administered directly following the POMS. The subjects were presented with a computer screen containing a series of 100-mm lines drawn horizontally with adjectives at each end. They were asked to mark somewhere between "not at all" and "extremely" in respect to their alertness, concentration, anxiety, energy, confidence, irritability jitteriness, sleepiness, and talkativeness levels. This computerized test took approximately 5 minutes.

The RTSW occurred every 6 hours. On practice and control days, test times were at 0820, 1420, and 2020. On the deprivation day, tests occurred at 0220, 0820, 1420, and 2020. Subjects were asked to lie on a bed in a quiet, dark room. They were instructed as follows "lie as still as possible with your eyes closed and do your best to remain awake." During the RTSW, EEG data were recorded from electrode sites C3, C4, O1, and O2 referenced to the contralateral mastoid. Subjects were allowed to remain in bed until 20 minutes had elapsed or until stage 2 sleep, as evidenced by a k complex or sleep spindle. The elapsed time from lights out was recorded.

Table 1.
Testing Schedule.

<table>
<tr><th>TIME</th><th colspan="4"></th><th></th></tr>
<tr><th></th><th>Day 1</th><th>Day 2</th><th>Day 3</th><th>Day 4</th><th>Day 5</th></tr>
<tr><td>2400</td><td></td><td>|
|</td><td>MINISIM
Late Snack</td><td>|
|</td><td>|
|</td></tr>
<tr><td>100</td><td></td><td>|
|</td><td>Vitals/PV/SSQ
SYNWORK</td><td>|
|</td><td>|
|</td></tr>
<tr><td>200</td><td></td><td>|
S</td><td>Electrode Check
RTSW</td><td>|
S</td><td>|
S</td></tr>
<tr><td>300</td><td></td><td>L
E</td><td>Baseline
Flight 1</td><td>L
E</td><td>L
E</td></tr>
<tr><td>400</td><td></td><td>E
P</td><td>Vitals/PV/SSQ
MATB</td><td>E
P</td><td>E
P</td></tr>
<tr><td>500</td><td></td><td>|
|</td><td>Postural Test
WOMBAT</td><td>|
|</td><td>|
|</td></tr>
<tr><td>600</td><td></td><td>|
|</td><td>MINISIM
Synwork</td><td>|
|</td><td>|
|</td></tr>
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Electrode Check</td><td>Vitals/PV/SSQ
Electrode Check</td><td>Wake up
Unhook/Release</td></tr>
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RTSW</td><td>Breakfast
RTSW</td><td>Breakfast
RTSW</td><td></td></tr>
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Flight 1</td><td>Fatigue
Flight 1</td><td>Control
Flight 1</td><td></td></tr>
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MATB</td><td>Vitals/PV/SSQ
MATB</td><td></td></tr>
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WOMBAT</td><td>Postural Test
WOMBAT</td><td></td></tr>
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Lunch</td><td>MINISIM
Lunch</td><td>MINISIM
Lunch</td><td></td></tr>
<tr><td>1300</td><td></td><td>Vitals/PV
SYNWORK</td><td>Vitals/PV
SYNWORK</td><td>Vitals/PV
SYNWORK</td><td></td></tr>
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RTSW</td><td>Electrode Check
RTSW</td><td>Electrode Check
RTSW</td><td></td></tr>
<tr><td>1500</td><td></td><td>Practice
Flight 2</td><td>Fatigue
Flight 2</td><td>Control
Flight 2</td><td></td></tr>
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MATB</td><td>Vitals/PV/SSQ
MATB</td><td>Vitals/PV/SSQ
MATB</td><td></td></tr>
<tr><td>1700</td><td>Informed Consent
Medical Review</td><td>Postural Test
WOMBAT</td><td>Postural Test
WOMBAT</td><td>Postural Test
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<tr><td>1800</td><td>Lab Tour
|</td><td>PT
Shower</td><td>PT
Shower</td><td>PT
Shower</td><td></td></tr>
<tr><td>1900</td><td>Dinner
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|</td><td>Dinner
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RTSW</td><td>Electrode Check
RTSW</td><td>Electrode Check
RTSW</td><td></td></tr>
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Flight 3</td><td>Fatigue
Flight 3</td><td>Control
Flight 3</td><td></td></tr>
<tr><td>2200</td><td>Hook up
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MATB</td><td>Vitals/PV/SSQ
|</td><td>Vitals/PV/SSQ
|</td><td></td></tr>
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|</td><td>Postural Test
WOMBAT</td><td>Bed Time
|</td><td>Bed Time
|</td><td></td></tr>
</table>

PV=POMS and VAS

Simulator flights

The flight profile simulated a UH-60 flying a mail delivery route that included stops at several remote sites. An onboard simulator operator provided frequent cueing to the subject-pilot throughout the profile to ensure proper timing and standardization of the flight maneuvers, and marked the beginning and ending point of each individual maneuver for the purpose of delimiting subsequent computer maneuver analysis. The profile took approximately 60 minutes to fly. The flights occurred every 6 hours. On practice and control days, flight times were at 0900, 1500, and 2100. On the deprivation day, tests occurred at 0300, 0900, 1500, and 2100. As the majority of SD accidents occur at night (Braithwaite et al., 1997), all flights were flown under simulated dusk conditions regardless of the actual time of day. The flight evaluations required pilots to perform precision maneuvers typically flown in a UH-60 (see table 2). There were a total of 26 tasks, which contained 10 standardized flight maneuvers, in this flight profile. These maneuvers consisted of one hover, one 180^0 hovering turn, two standard-rate climbs, two standard-rate turns, two straight-and-levels, and two standard-rate descending turns.

During each of the maneuvers, excluding the hover and hovering turn, the subjects were required to maintain an airspeed of 120 knots. The specific targets for other parameters such as heading, altitude, roll, slip, etc. changed depending upon which maneuver was being flown. Subjects attempted to maintain appropriate ideal flight parameters during each maneuver. The scores represented the average control accuracy across all of the parameters important to each maneuver or type of flight. A score of 100 denoted perfect flight accuracy.

Spatial disorientation events

One SD event (pitch, drift, or roll) occurred during each fatigued and rested flight. These events have been previously tested (LeDuc et al., 1999). The computer time-stamped the onset of each SD event. Following the onset of each event, the simulator operator instructed the pilot to recover to the original course heading, altitude and airspeed. In the case of a drift event during landing, the pilot was instructed to establish a 10' stabilized hover over the landing point on the original heading. When these criteria were met, the simulator operator again time-stamped the data stream. The time from event onset to the time that the aviator had re-established the original flight parameter was used as flight recovery time.

A roll event occurred during task 9 where visuals moved left and motion moved right at a 6^0 per sec divergence. A roll also occurred during task 22 where visuals rolled right and motion rolled left. This event occurred over hilly terrain and was designed to give the impression that the aircraft was rolling into a hill. A pitch event where the visuals moved up and motion moved down at a 4^0 per sec divergence occurred during task 11. A pitch event also occurred at task 21 where visuals moved down and motion moved up. This event occurred during low level flight and gave the impression that the aircraft was nosing into the ground. As each aviator began to land during task 13, visuals moved right and motion moved left at an 8^0 per sec divergence causing an apparent aircraft drift. A drift event was also produced as each aviator began to land during task 25, where visuals moved left and motion moved right.

Table 2.
Flight Profile.

Task #	Description	Time (SEC)	Heading (DEG)	Altitude (FEET)	Airspeed (KIAS)	Event Type
1	Hover	60	090	10' AGL	0	
2	Hovering Turn	60	090>090	10' AGL	0	
3	Low Level Navigation	240	086	700' MSL	120	
4	Climb	60	100	700>1200' MSL	120	
5	Right Standard Rate Turn	60	100>280	1200' MSL	120	
6	Straight and Level	60	280	1200' MSL	120	
7	Descending Right Turn	60	280>100	1200>700' MSL	120	
8	Nap of the Earth	180	344	25' AGL	120	
9	Contour	180	031	80' AGL	120	Roll
10	Landing	120	015	N/A	N/A	
11	Nap of the Earth	240	338	25' AGL	120	Pitch
12	Contour	120	296	80' AGL	120	
13	Landing	120	255	N/A	120	Drift
14	Contour	240	319	80'AGL	120	
15	Contour	120	250	80'AGL	120	
16	Climb	60	200	1000>1500' MSL	120	
17	Left Standard Rate Turn	60	200>020	1500' MSL	120	
18	Straight and Level	60	020	1500' MSL	120	
19	Descending Left Turn	60	020>200	1500>1000' MSL	120	
20	Contour	180	173	80' AGL	120	
21	Contour	240	066	80' AGL	120	Pitch
22	Contour	120	076	80' AGL	120	Roll
23	Contour	120	181	80' AGL	120	
24	Contour	240	214	80' AGL	120	
25	Landing	120	180	N/A	N/A	Drift
26	Nap of the Earth	240	249	25' AGL	120	

DEG=Degrees, KIAS=Knots indicated airspeed, AGL=Above ground level, MSL=Mean sea level.

Cognitive performance evaluation (WOMBAT)

The 30-minute WOMBAT was administered at 1130 and 1710 on practice and control days and at 2330, 0530, 1130, and 1730 on the deprivation day. Two Worth and Performance indicators were always visible in the top corners of the display and served as guides to the subject in making the proper choices, establishing the best strategy and monitoring scoring progress. The left indicator related to the primary task (target tracking), and the right indicator showed the secondary task (or Bonus) performance level.

The product of the Worth and Performance indicators represented the current effectiveness and was computed into an index of recent effectiveness that was also continuously displayed for the subject. An indication of total current points and a prediction of the final score (the "E" mark), based on current points plus current effectiveness extrapolated from the time remaining, complete the total scoring display. While performing the WOMBAT test, the subject received constant feedback and extrapolated outcome based on his/her previous choices. The subject was expected to make good use of this data in determining the best course of action.

Cognitive performance evaluation (MATB)

Following the SSQ, subjects completed a 30-minute session on the MATB. The MATB was administered every 6 hours beginning at 1030. On practice and control days, test times were 1030 and 1630. During the deprivation period, tests were given at 2230, 0430, 1030 and 1630. Subjects were required to monitor and respond to several tasks that are presented simultaneously on the computer screen. The test is an aviation-oriented simulation that presents indications of fuel levels, engine conditions, and pumps that the subject must correctly monitor to ensure normal "flight operations." In addition, the subject concurrently performed a psychomotor tracking task and responded to instructions to periodically change radio frequencies. This test yielded a variety of speeds and accuracy scores for each subtask.

Cognitive performance evaluation (SYNWORK)

On the practice and control day, the test time was at 1330. On deprivation day, tests were given at 0130, 0645, and 1330. In the 20-minute SYNWORK, the memory, arithmetic, visual and auditory monitoring tasks ran concurrently in four quadrants of a computer screen. The Sternberg memory task, in the upper left corner, presented subjects with six letters. The letters were removed from view a few seconds after presentation. Letters were then presented one at a time and subjects were required to indicate if each letter was part of the initial six-letter set. A three column addition task, presented in the upper right hand corner, required subjects to add two numbers totaling less than 1000. The visual monitoring task, presented in the lower left corner, required a subject to reset a pointer, which moved from the center of a scale in either direction, prior to it reaching the end. The auditory monitoring task, presented in the lower right corner, required subjects to respond when a high tone was presented among a series of low tones. All responses were made using a mouse in order to avoid keyboard distractions. A subject's score was visible in the center of the screen providing constant feedback.

Desktop flight performance

Following the WOMBAT, the subjects completed a 20-minute MINISIM session. The test was given at 1210 on the practice and baseline days, and at 2410 and 0610 on test days. This task required the subjects to fly a timed course consisting of 21 "gates" positioned at various altitudes and headings. The first 15 gates were flown under nonturbulent conditions, while gates 16-21 were made more difficult by the addition of 20-knot winds emanating from various directions. This task produced a summary score at the conclusion of each "flight." The score was calculated automatically from the elapsed time it takes to fly the course, the number of gates missed, and the precision with which the subjects flew through each of the gates.

Postural test

An initial posturography test was given on Monday evening following electrode hook up. Postural tests were then given at 1110 and 1710 on practice and control days and at 2310, 0510, 1110, and 1710 on the deprivation day. Previous research (McGrath, Rupert and Ruck, 1993; McGrath et al.1994) has led to the development of the U. S. Navy Aerospace Medical Research Laboratory (NAMRL) protocol, which incorporates systematically timed and oriented head movements during the Sensory Organization Tests (SOTs). The NAMRL protocol involves a series of controlled left/right and fore/aft dynamic head movements during the 20 seconds of the SOT trials. The movements consist of laterally flexing the head down to the left shoulder, back to upright, then to the right shoulder, back to upright, pitching the head forward, back to upright, tilting the head back, and finally returning the head back to the upright. The subject was asked to tilt his/her head as far as possible in each direction without putting strain on the neck or moving the shoulders. Subjects were encouraged to make the same magnitude and range of motion for each set of tests. The operator provided commands to achieve a constant frequency of head movements. The commands were given in response to a computer prompt at the times in parentheses from the beginning of SOT 1: left (3 seconds), up (5), right (7), up (9), forward (11), up (13), back (15), and up (17). SOT equilibrium scores were based on the assumption that a normal individual can exhibit anterior to posterior sway over a total range of 12.5 degrees (6.25 degrees anterior, 6.25 degrees posterior) without losing balance. The equilibrium score compared subject sway in a 20-second period to the theoretical limits of stability for normal subjects. The score divided by the theoretical limit score is expressed as a percentage between 0 and 100, where a score of 0 indicates a fall and 100 denotes perfect stability.

Data analysis

All of the data from this investigation were analyzed with BMDP4V repeated measures analysis of variance (ANOVA). Where there were significant interactions, analyses of simple effects and contrasts were employed to pinpoint differences. Main effects that occurred in the absence of higher-order interactions were examined using pairwise comparisons. All ANOVAs consisted of at least the two within-subjects factors, condition (fatigued or rested) and session (at least three test sessions). The number of sessions varied based upon how many times per day each test was administered.

Prior to analysis, the data were examined for completeness, and any missing data were estimated with BMDPAM. At that time, normality was checked. Once the ANOVAs were conducted, the results were examined to determine whether there were sphericity violations of sufficient magnitude to warrant the use of Huynh-Feldt adjusted degrees of freedom (dfs). If appropriate, the adjusted dfs were employed.

Due to the fact that there were not sufficient cases to produce meaningful multivariate tests, univariate ANOVAs were conducted on the data from each of the categories of dependent measures examined in this study. Flight performance data consisted of scores calculated from each relevant parameter (i.e., heading, airspeed, and altitude) for each maneuver. Recovery times for each SD event were analyzed separately. The desktop flight simulator data consisted of one composite score per flight. The POMS data consisted of scores from each of the six test scales. The VAS data consisted of scores from each of the eight adjectives. Scores from each of the MATB and WOMBAT subtasks were analyzed separately. SYNWORK composite scores representing overall performance on each of the subtasks were separately analyzed. The RTSW data were scored from lights out until a subject entered stage 1 and stage 2 sleep. Data from the postural test consisted of percent stability scores.

Results

SSQ

An ANOVA using two factors, condition (fatigued and rested) and session (0715, 1015, 1315, 1615, and 2215), showed that there was no main effect for session or a session by condition interaction. There was a main effect for condition on all measures of the SSQ, to include the nausea ($F(1,7)=13.53, p<.008$), oculomotor ($F(1,7)=20.86, p<.003$), disorientation ($F(1,7)= 12.11, p=.01$), and total symptom severity scores ($F(1,7)=19.55, p=.003$). All scores were significantly higher during the fatigued than during the rested condition (see figure 1).

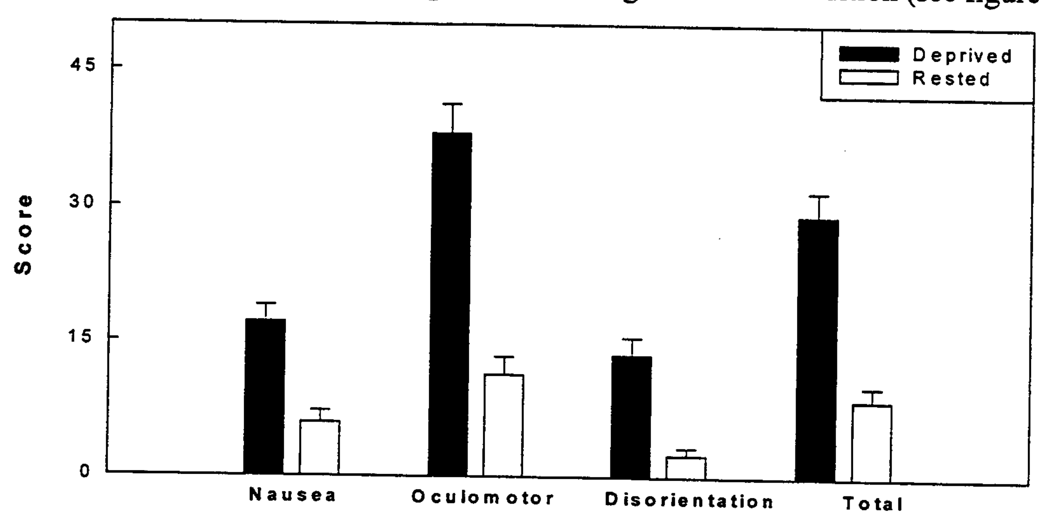


Figure 1. Effect of condition on simulator sickness symptoms.

Mood evaluations

Analysis of POMS data revealed a main effect for condition on all six factors (tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment). Subjects reported being significantly more tense ($F(1,7)=13.73, p<.008$), depressed ($F(1,7)=13.00, p<.009$), angry ($F(1,7)=8.56, p=.02$), fatigued ($F(1,7)=30.08, p<.001$), and confused ($F(1,7)=22.77, p=.002$), as well as feeling less vigorous ($F(1,7)=14.06, p=.007$), during the fatigued condition (figure 2).

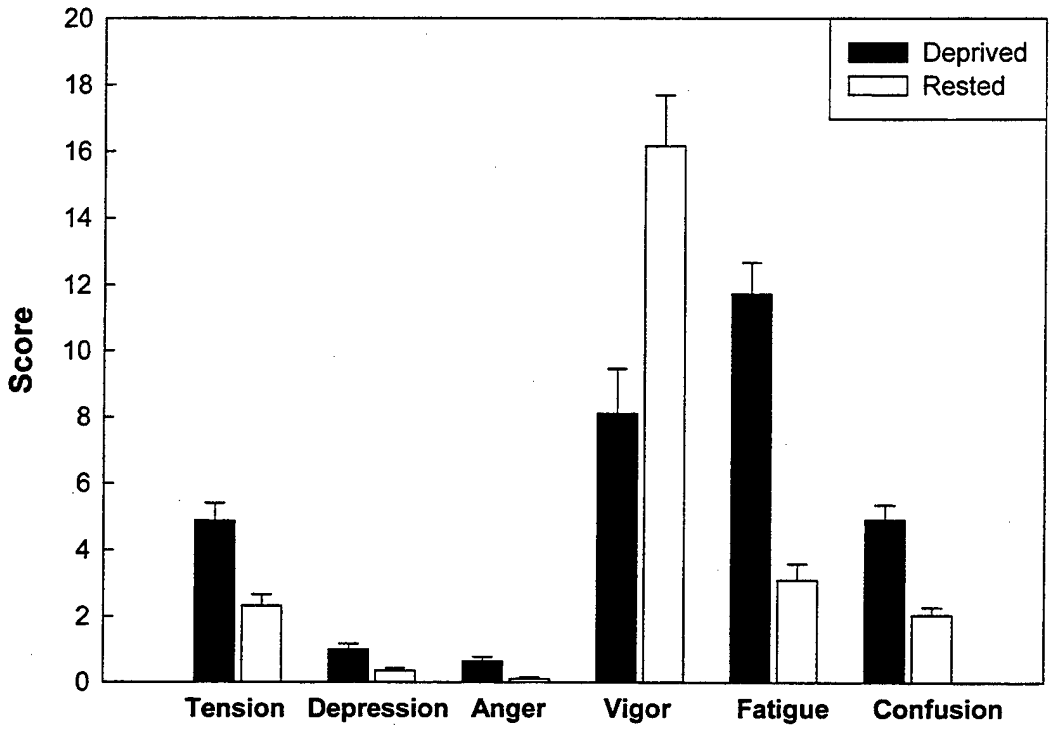


Figure 2. Effect of condition on self-reported mood states.

A main effect for session (0720, 1020, 1320, 1620, and 2220) was also observed on the anger-hostility ($F(4,28)=3.53, p<.02$) and confusion-bewilderment ($F(4,28)=2.68, p=.05$) factors. Subjects reported higher levels of confusion during the morning sessions (0720 and 1020) than during the later sessions. Additionally, the highest level of anger-hostility was reported during the early morning (0720) session. Anger-hostility ratings decreased at the 1020 session and remained at level throughout testing. No significant condition by session interaction on these or any of the other POMS factors was observed.

Sleepiness evaluations

Analysis of the subjective VAS data revealed main effects for session and condition, but no interaction of these variables. The main effect for session was only seen with the self-reported alertness scores ($F(4,28)=3.63, p<.02$). Alertness was lowest during the morning sessions (0725 and 1025), increased sharply at the 1325 session and declined again during the final two sessions. Despite the decline during the 1625 and 2225 sessions, levels did not return to the early morning low.

A main effect for condition was seen on four of the eight sleepiness measures on the VAS. Subjects reported being less alert ($F(1,7)=20.04, p<.003$), energetic ($F(1,7)=23.99, p<.002$), and confident ($F(1,7)=22.65, p<.003$) during the fatigued condition than during the rested condition (figure 3). Aviators also reported that they felt significantly more sleepy ($F(1,7)=28.33, p<.001$) during the deprivation period.

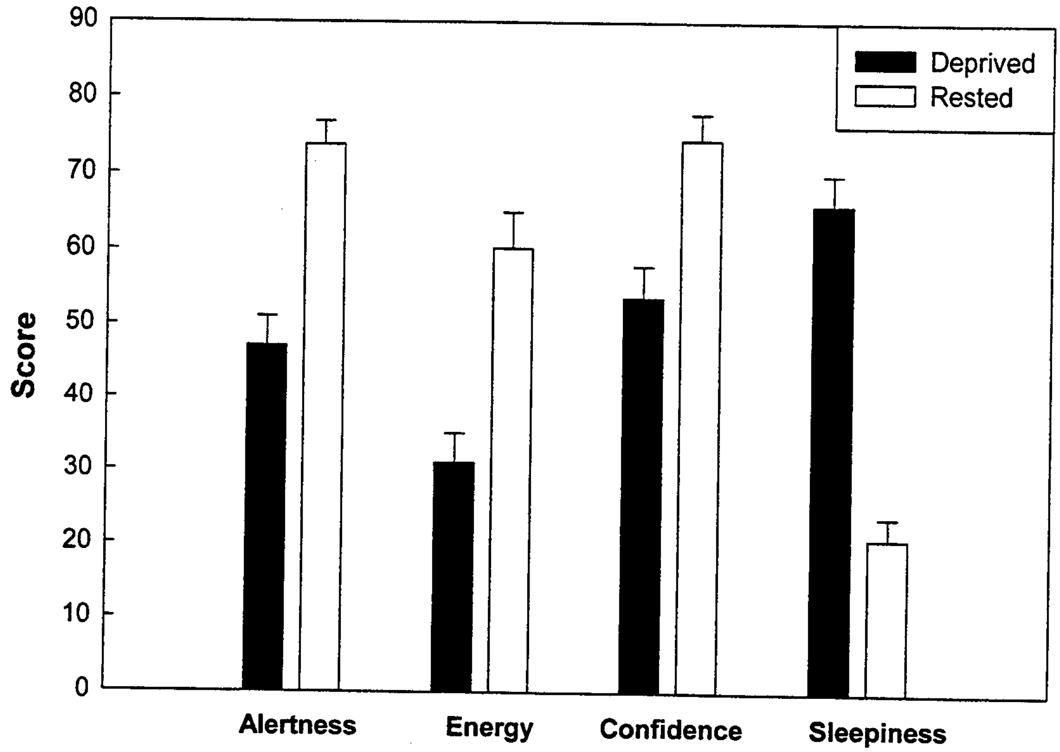


Figure 3. Effect of condition on self-reported sleepiness.

Analysis of the RTSW data (latency to Stage 1 and Stage 2 sleep) revealed main effects for session and condition, as well as an interaction of these variables. The session main effects were seen in latency to Stage 1 sleep ($F(2,14)=7.58, p<.006$) and Stage 2 sleep ($F(2,14)=5.43, p<.02$). Both of these main effects were due to the fact that aviators fell asleep significantly faster during the midafternoon session (1420) than during either the early morning (0820) or evening (2020) session. The main effect for condition was due to significantly shorter latencies to Stage 1 ($F(1,7)=22.82, p=<.003$) and Stage 2 sleep ($F(1,7)=23.01, p=.002$) in the fatigued condition than during the rested condition (figure 4, upper right).

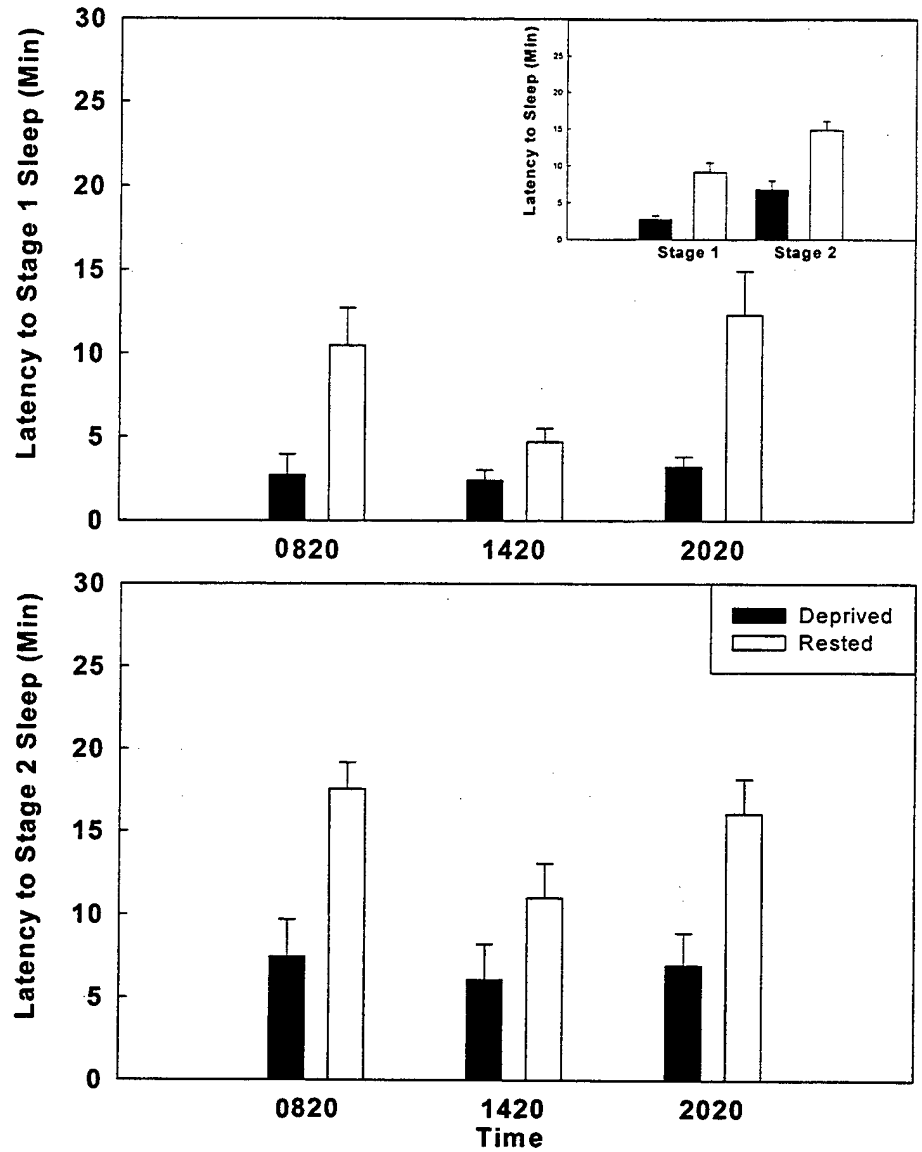


Figure 4. Effects of condition (upper right graph) and the interaction of condition and session on the latency to Stage 1 (upper panel) and Stage 2 sleep (lower panel).

Simple effects and contrasts of the interaction of condition and session for Stage 1 sleep ($F(2,14)=10.62, p<.002$) revealed that changes across sessions were only significant during the rested condition (figure 4, top panel). The latency to Stage 1 sleep significantly declined from 10.5 minutes during the early morning session to 4.7 minutes during the midafternoon session. Sleep latency then increased to 12.3 minutes by the 2020 session. Simple effects and contrasts of the interaction of condition and session for latency of Stage 2 sleep ($F(2,14)=3.89, p<.05$) showed changes similar to those of Stage 1. Sleep latency declined from the 0820 session to the 1420 session and then increased during the 2020 session (figure 4, bottom panel).

Flight Performance

The time from event onset to reestablishment of the original flight parameter (e.g. airspeed, heading, and radar altimeter) following an SD event was defined as recovery time. The factors used in the analysis were condition (fatigued and rested) and event (pitch, drift, and roll). The analysis revealed a main effect for condition ($F(1,7)=13.92, p<.008$). This was due to the fact that it took the aviators significantly longer to recover from the events during the fatigued condition (90.5 seconds) when compared to the rested condition (78.0 seconds). A main effect for event was also seen ($F(1,7)=96.77, p<.001$). Contrasts showed that it took subjects significantly longer to recover from the drift event (127.9 seconds) than either the pitch (61.8 seconds) or the roll (63.1 seconds). While no condition by event interaction was found, the data are graphically depicted in this format for ease of visual examination (figure 5).

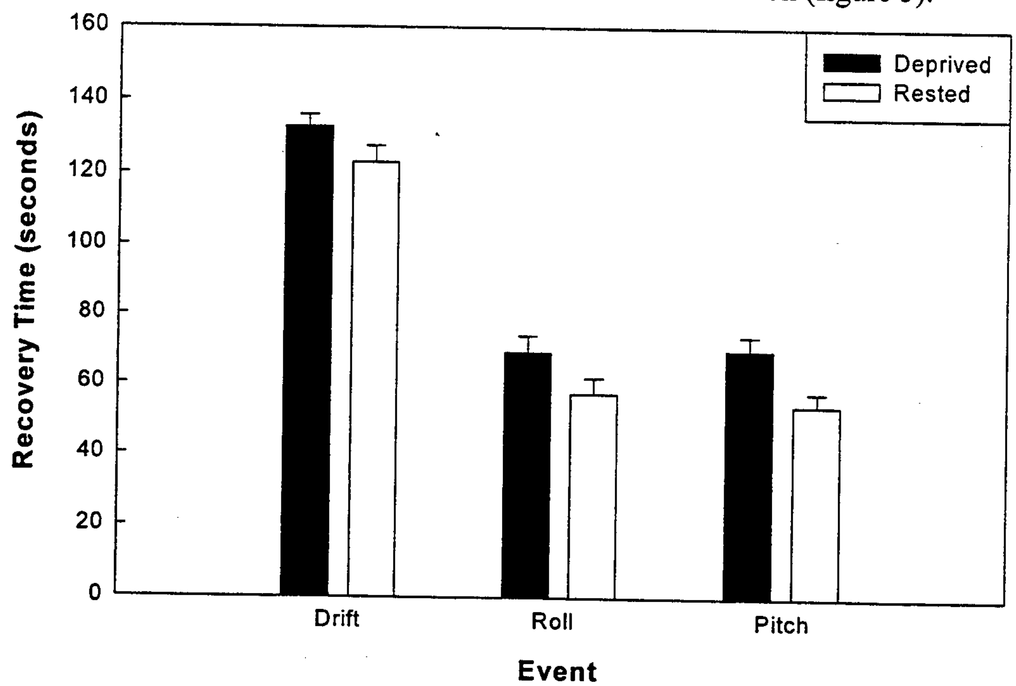


Figure 5. Effects of condition and event type on time to recovery of original flight parameters.

Data from the standard maneuvers (i.e., straight and level, hover, hovering turn), nap of the earth flight, and contour flight were separately analyzed. Flight performance data consisted of scores which represented the average control accuracy across all of the parameters (i.e., heading, airspeed, slip, roll, and altitude) important to each maneuver or type of flight. A score of 100 denotes perfect flight accuracy. The flight performance scores were analyzed with 2-way ANOVAs using the factors condition (fatigued and rested) and session (0900, 1500, and 2100).

Analyses of the standardized maneuvers revealed significant differences only on the hover. A main effect for condition was seen ($F(1,7)=5.33, p=.05$). This was due to the fact that aviators were not able to control the aircraft as well when they were fatigued (figure 6, top panel). No session main effect or condition by session interaction was observed on this maneuver.

Analyses of the nap of the earth and contour flight legs revealed significant differences only during contour flight. A main effect for condition was seen in the contour flight scores ($F(1,7)=14.65, p<.007$). Scores during the fatigued condition averaged 32.8, and averaged 36.7 during the rested condition (figure 6, bottom panel). The differences in scores were attributable to the fact that aviators tended to fly at more variable altitudes (as measured by radar altimeter) when they were fatigued, despite instructions to remain at an altitude of 80 feet as prescribed for contour flight. No session main effect or condition by session interaction was observed on this type of flight.

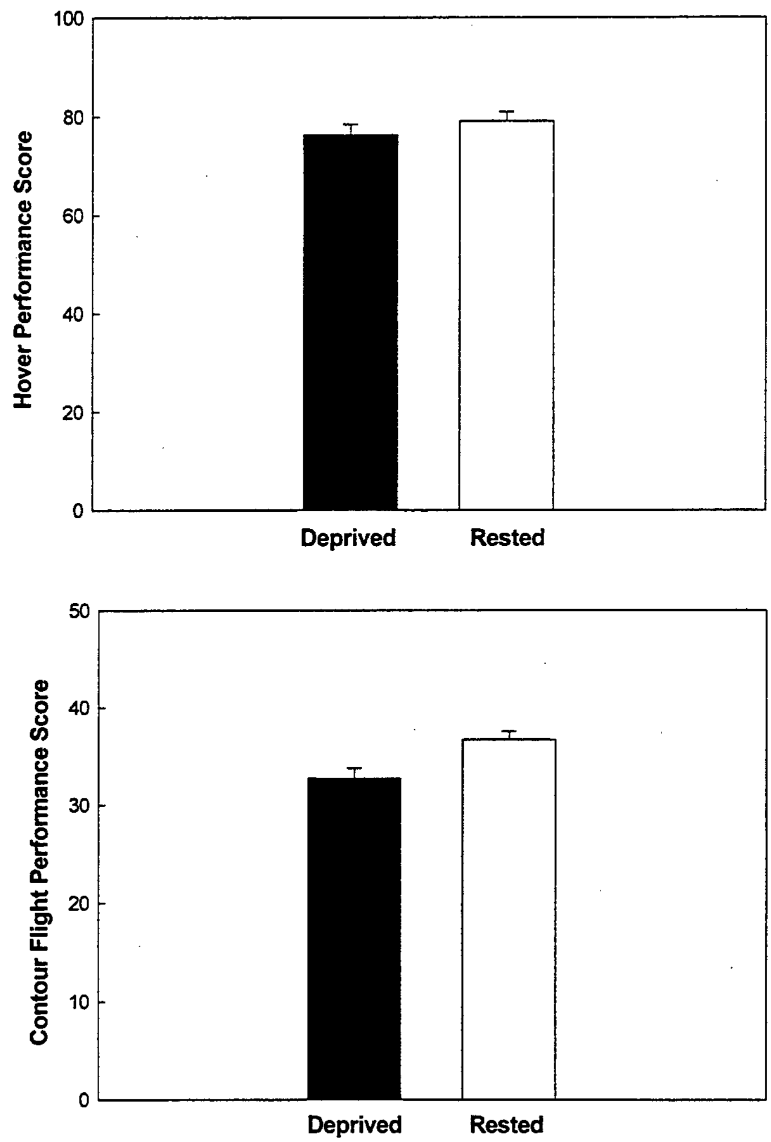


Figure 6. Effect of condition on hover (upper panel) and contour flight (lower panel).

Cognitive performance evaluations

WOMBAT

Analysis of WOMBAT data revealed a significant main effect for condition on several of the secondary bonus subtasks. These effects are presented in figure 7. Performance on the 3-D figure rotation task was degraded when the aviators were fatigued ($F(1,7)=8.75, p=.021$). Quadrant location, where subjects had to cancel patterns of numbers scattered in four quadrants of the computer screen, was also impaired by sleep loss ($F(1,7)=8.41, p=.023$). Additionally, subjects were less able to detect the patterns within the quadrant location task when fatigued; thus decreasing the number of sequences mastered during the test ($F(1,7)=11.19, p=.012$). Due to the decrements on the 3-D and quadrant location tasks, total bonus points were significantly reduced following sleep loss ($F(1,7)=7.06, p=.033$). No main effects for session or condition by session interactions were observed.

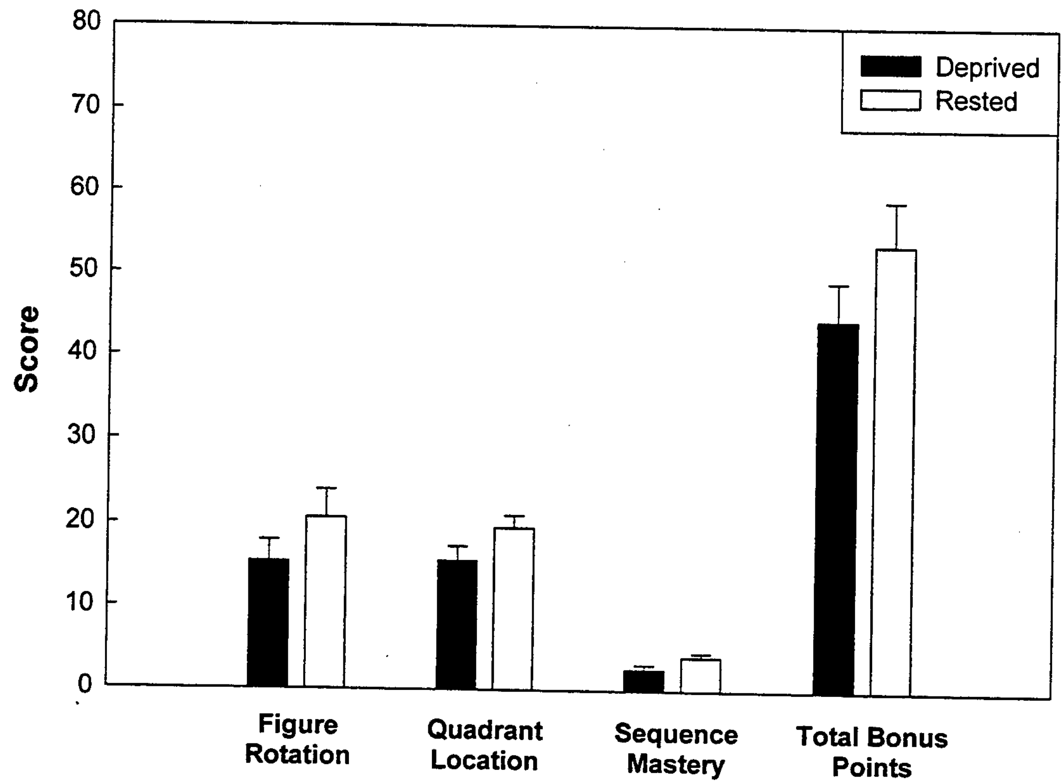
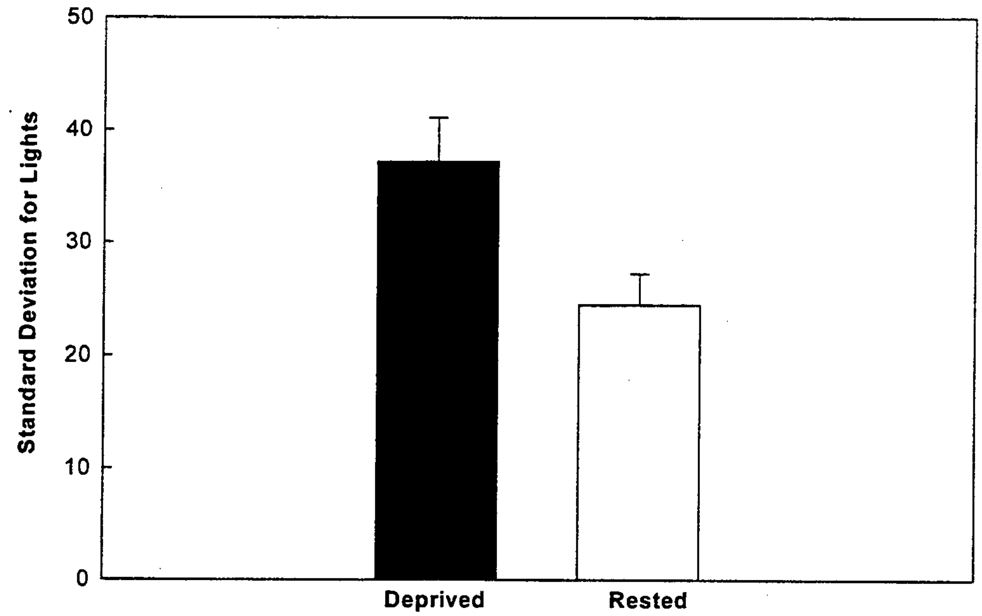


Figure 7. Condition effect on WOMBAT secondary tasks.

MATB

Data were subjected to ANOVAs using the factors condition and session. Analysis showed a condition main effect for two variables, standard deviation of response time to lights ($F(1,7)=24.16, p<.002$) and fuel management ($F(1,7)=5.34, p=.05$). Standard deviation of response time to lights showed that subjects were much more variable in their responses during the fatigued condition (figure 8, top panel). Additionally, subjects did not manage fuel consumption in the various tanks as well when they were sleep deprived (figure 8, bottom panel). There was no main effect for session and no significant condition by session interaction.



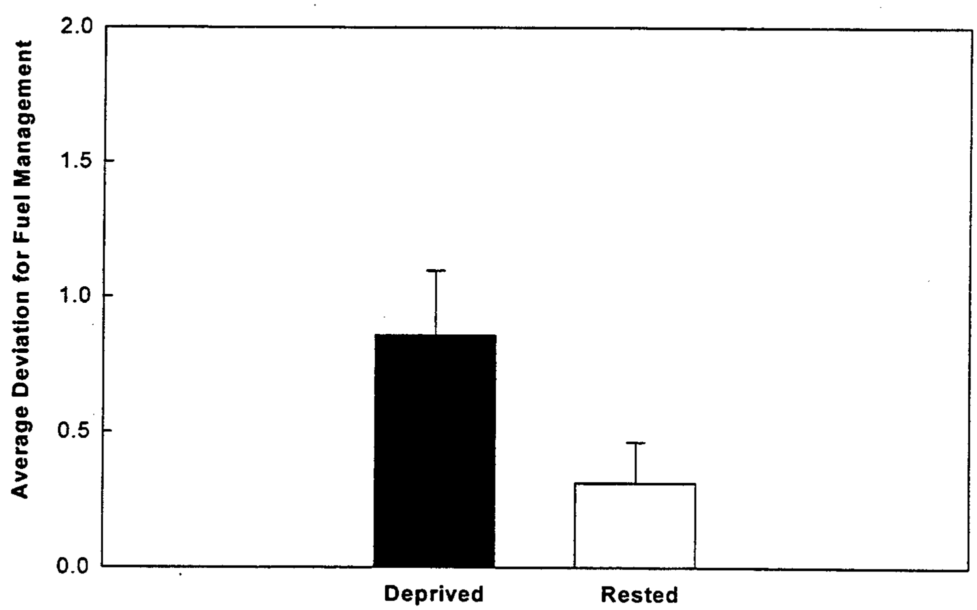


Figure 8. Effects of condition on the standard deviation in response to lights (upper panel) and the average deviation in fuel tank management (lower panel).

SYNWORK

Data were subjected to an ANOVA using the factor condition. Analysis showed a condition main effect for two variables, positive tones detected ($F(1,7)=8.77, p=.02$) and percent of signals detected ($F(1,7)=8.80, p=.021$). Analysis showed that the subjects detected fewer positive tones when they were fatigued than when they were rested; thus decreasing the percent of signals detected (figure 9).

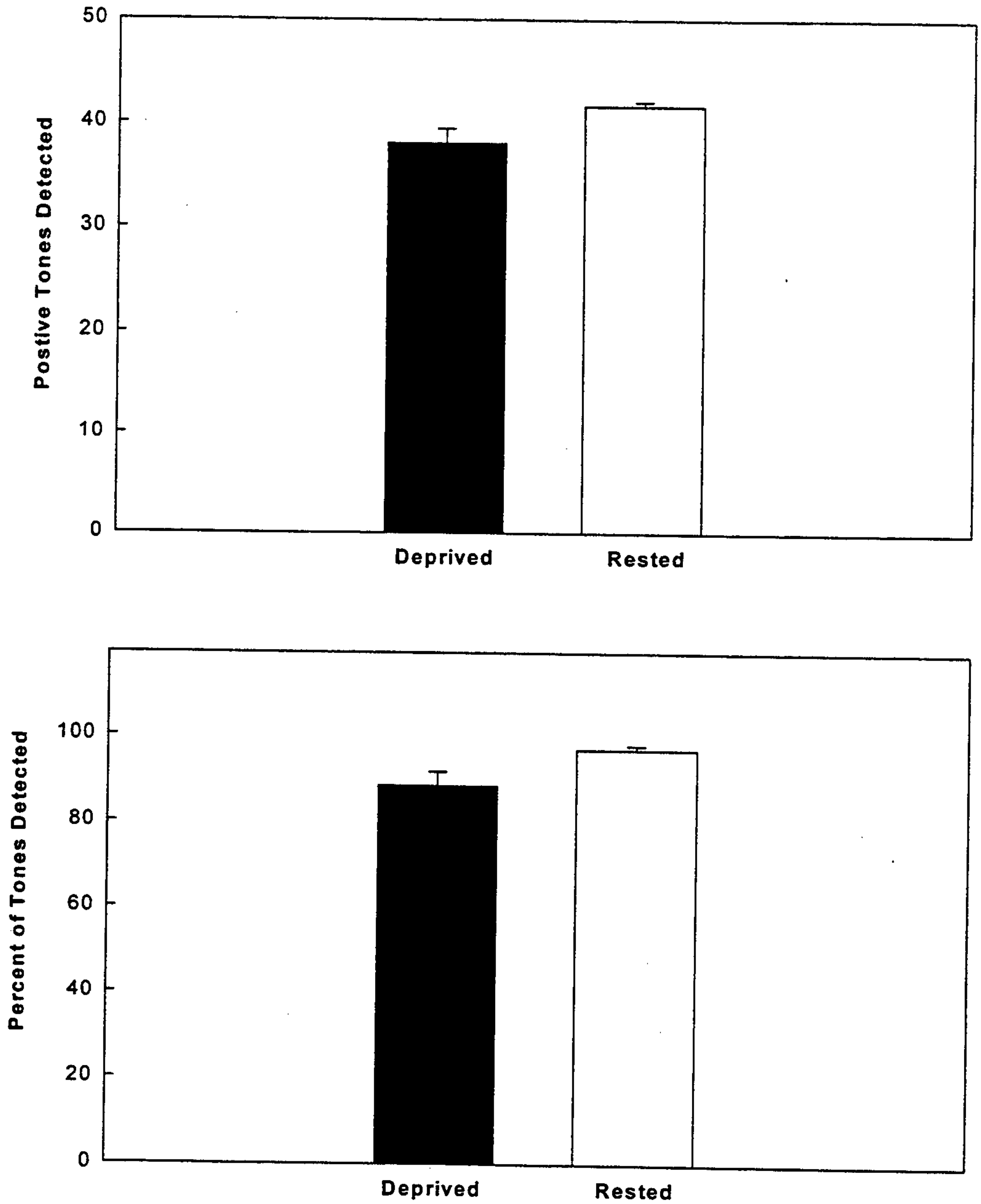


Figure 9. Condition effect on response to positive tones (upper panel) and the percent of tones detected (lower panel).

Desktop flight performance

Analysis of the variables elapsed time, speed, and score found no differences between the fatigued and rested conditions. It took the subjects relatively the same amount of time to fly the course, they flew at consistent speeds, and flew through the same number of target gates under both conditions.

Postural tests

A three-way ANOVA was run on the postural data using the factors condition (fatigued and rested), session (1130 and 1730), and eyes (opened and closed). The analysis revealed a main effect for condition ($F(1,7)=5.03, p=.05$) and a main effect for eyes ($F(1,7)=1.07, p<.001$). Aviators had a more difficult time maintaining their balance when they were fatigued (figure 10). Additionally, regardless of condition, balance was worse under the eyes closed condition than when the subjects had their eyes open. Analysis also showed that there was no main effect for session and no interactions among the three factors.

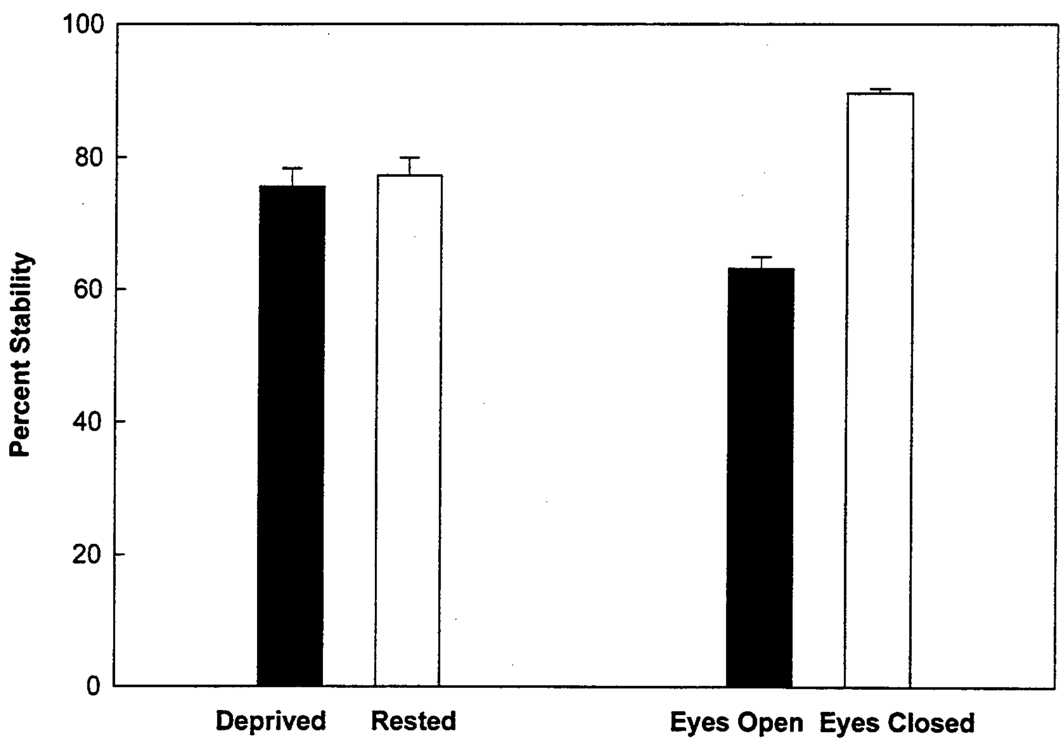


Figure 10. Effect of condition and effect of eyes closed verses eyes open on postural stability.

Discussion

This investigation was conducted to examine the effects of fatigue on various aspects of performance, specifically those that can seriously impact flight abilities. This study employed a variety of assessments to determine the effects of fatigue on orientation, cognitive performance, mood, and alertness. Additionally, aviator response to in-flight disorientation and standard flight maneuvers of the type typically conducted in the UH-60 aircraft were examined under rested and fatigued conditions. In general, few circadian-related effects were seen across the daily sessions. However, nearly all measures of performance, mood, and alertness were affected by fatigue.

The differences observed on several measures between the rested and fatigued conditions suggested that spatial orientation was detrimentally impacted by fatigue. The SSQ subscore for disorientation in this study averaged 2.4 during the rested condition. However, during the fatigued condition the average disorientation score increased by more than five times to 13.6. According to Kennedy et al. (1992), anyone with scores over 15 on any of the scales should talk with a physician about the expected time course of symptom dissipation. While the disorientation score did not exceed one standard deviation (15), it was very close and would be cause for concern.

As with the SSQ, examination of postural stability showed that aviators had a more difficult time maintaining their balance when they were fatigued. Postural instability (ataxia) has been noted by several researches when assessed directly following simulated flight (Crosby and Kennedy, 1982; Gower and Fowlkes, 1989; Gower et al., 1987). In this study, there was a 60-minute lag between the end of the flight and the postural stability test. Given this time lag, it would seem unlikely that the decrease in postural stability during the fatigued condition was due entirely to symptoms produced by simulated flight, as no instability problems were seen following flights during the rested condition.

A third, and perhaps more important, measure of spatial orientation was flight performance. Fatigue induced decrements were seen in flight accuracy on two of the most common, yet critical flight tasks, hover and contour flight. During the stationary hover maneuver, aviators were not able to control the altitude or heading parameters as well as during the fatigued condition. A recent examination of U.S. Army accident data by the U.S. Army Safety Center identified drift during hover as a significant flight hazard. Over the past 5 years, more than 15% of rotary-wing accidents have occurred as a result of aircraft drift (personal communications with CPT Robert Wildzunas, U.S. Army Safety Center). It is especially difficult to notice drift during a hover under less than optimal visual conditions, as were used in this study (simulator visuals were set for dusk). Thus, one recommendation made by the panel assembled by the U.S. Army Safety Center was to equip all rotary-wing aircraft with hover-hold such as seen in the Apache.

Another significant flight hazard identified by the U.S. Army Safety Center was obstacle strikes during slow, low level flight. A combination of obstacle strikes during hovers and low level flight accounted for more than one half of all Army rotary-wing accidents over the past 5 years. As discussed earlier, the average scores obtained from the contour flight segments (low level flight) were significantly worse during the fatigued condition due to more variability in altitude than the established parameter of 80 ft. This is not unusual as it has been shown that aviators have a tendency to overestimate altitude in the UH-60 simulator when flying at low altitudes relying on sensory cues only (Crowley et al., 1996). These authors also found that following training, aviators tended to underestimate altitude when flying the same flight profile. While aviators in the present study were not forced to fly using only perceptual cues, it is possible that fatigue negatively impacted depth perception.

It has long been hypothesized that one function of rapid eye movement sleep is to give the oculomotor system periodic stimulation which helps maintain normality of binocularly coordinated eye movements (Berger, 1969). It has repeatedly been demonstrated that periods of sleep deprivation can produce opthalmological decrements such as nytagmus, diplopia, myopia, decreased accommodation, and reduced binocular convergence (Clark and Warren, 1939; Kleitman and Schneider, 1940; Paul, 1965; Sassin, 1970). As coordinated eye movements are an important part of depth perception, aviators in this study may have had a more difficult time judging altitude because of opthalmological difficulties during the sleep deprived flights. This idea is supported by the fact that aviators reported more than a threefold increase on the oculomotor disturbance scale of the SSQ following fatigued simulator flights when compared to flights following a night of sleep.

In addition to performance decline on standard flight maneuvers, it took the aviators significantly longer to recover from the SD events during the fatigued condition (90.5 seconds) when compared to the rested condition (78.0 seconds). While a 12 second difference may not appear to be very large, it should be remembered that two of the events occurred while the aviators were flying at 120 knots. Much can happen to an aircraft in that length of time, at that speed. Additionally, the SD events used in this study were specifically designed to produce mild disorientation (roll 6^0/sec, pitch 4^0/sec, and drift 8^0/sec divergence) so that flight recovery, and not crashes, could be examined. The events themselves did not produce any crashes; however, a check of the simulator operators notes from each flight indicated that aviators hit trees, crashed on landing, missed waypoints, and were forced to do go-arounds twice as often during the flight profile when they were fatigued.

Several measures showed that aviators experienced significant declines in alertness and negative changes in mood during the fatigued condition. On the subjective alertness measure, the VAS, aviators reported being less alert, less energetic, and sleepier during the fatigued condition. On the subjective measure of mood, the POMS, aviators reported that they felt significantly more tense, depressed, angry, fatigued, and confused, as well as less vigorous during the fatigued condition. The objective measure of alertness, the RTSW, also showed significant declines in alertness. The latencies to Stage 1 sleep and Stage 2 sleep were significantly shorter in the fatigued condition, demonstrating that aviators had a much more difficult time remaining awake during the 20-minute test when subjected even to a short period of sleep loss. The typical circadian dip seen in the early afternoon during the rested sessions was not seen during the fatigued sessions. This was due to the fact that, on average, aviators entered

Stage 1 sleep in less than 3 minutes during the fatigue sessions. This is noteworthy considering that a sleep onset of less than 5 minutes on the Multiple Sleep Latency Test (a variant of the RTSW) is indicative of pathological levels of sleepiness (Carskadon, 1994).

As with most other measures, analysis of the cognitive tests indicated significant performance impairments during the fatigued condition. Both visual and auditory signal detection, tasks that require fairly low levels of cognitive functioning, were affected by fatigue. Subjects were much more variable in their responses to lights on the MATB and detected fewer positive auditory tones on the SYNWORK during the fatigued condition. These results also agree with the majority of the literature that has consistently shown increased variability in reaction times and decreases in performance on vigilance tasks with increasing periods of sleep deprivation (Dinges & Broughton, 1989; Dinges and Kribbs, 1991; Kjellberg; 1977a; b; c; McCarthy and Waters, 1997; Williams, Lubin, and Goodnow, 1959).

Additionally, aviators were not able to match the WOMBAT 3-D figures during the rotation task as quickly or as accurately when fatigued. Performance also suffered on the subtask where subjects had to cancel numbers scattered in four quadrants of the computer screen. Subjects were less able to detect the patterns within the quadrant location task when fatigued, thus decreasing the number of sequences mastered during the test. The fuel management task on the MATB, which requires subjects to turn pumps on and off throughout the test to ensure balanced fuel loads, was also negatively affected by fatigue. These tasks all require a fairly high level of cognitive processing, to include future planning in the fuel management. These data are in agreement with others who have shown that moderate amounts of sleep deprivation (32-48 hours) can produce impairments in higher level cognitive functioning needed for tests of creative thinking, decision making, and nonverbal planning (Babkoff et.al., 1985; Horne, 1988; 1991).

Conclusions

It was very apparent that fatigue had a negative effect on most types of performance. In particular, flight maneuvers, during which more than 50 percent of all Army rotary aircraft accidents occur, such as hovers and low level flight, were most effected by sleep loss. High and low levels of cognitive functioning were also impaired. It should be noted, however, that all of the cognitive assessments used in the present study were visually based tasks. As the average oculomotor disturbance score during the fatigued test period was 38.1 (>2 standard deviations), it is possible that visual problems accounted for the declines in both flight and cognitive performance. In order to apportion the amount of performance declines due to fatigue of the visual system, it will be necessary to obtain measurements of visual acuity, binocular convergence, accommodation, and other visual processes that may impact flight performance. Additionally, nonvisually based assessments of cognitive function must be incorporated into research examining the effects of fatigue on performance.

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Appendix

Manufacturers List

Aero Innovation Inc.
970 Montee de Lisse, Suite 210
Saint-Laurent QC H4T 1W7

CH Products
970 Park Center Drive
Vista, CA 92083

Microsoft
1 Microsoft Way
Redmond, WA 98952

NeuroCom® International, Inc.
9570 SE Lawnfield Road
Clackmas, OR 97015-9611